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Cryogenic Targets for Inertial Confinement Fusion

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Introduction - Do you really need *cryogenic* targets??

It is now generally accepted that the 'ideal' target configuration for inertial confinement fusion (ICF) is a spherical shell of low-z ablative material immediately surrounding a dense shell (aspect ratio of 5 to 10) of 50-50 D-T fusion fuel. The target designer typically assumes that the D-T is initially in either the liquid ($\rho = 0.22$ g/cm^3) or solid ($\rho = 0.25$ g/cm^3) state and that it has been confined to a perfectly smooth, symmetric layer by some kind of 'magic' of the target fabricator. That this particular geometry is currently in vogue, of the many which have been proposed over the past twenty years [for a discussion of several early high-gain target concepts, see Bodner (1981)], is a consequence of the immediate goals of the US National ICF program, namely to achieve ignition and propagating burn in the laboratory with the absolute minimum of incident energy. If the goal were, for instance, to achieve very high gain and robustness, as might someday be necessary for a commercial reactor, then it could be argued that other target geometries are more suitable. For example, the concept of volume ignition, once thought to be unsuitable for achieving high gain, has seen a recent resurgence of interest (Basko 1990).

However, reaching a gain of unity or greater with the absolute minimum of input energy restricts one to the concept of spark ignition, where most of the fuel is simply compressed *cold* to a high density, while only a small fraction is compressed *and heated* to fusion conditions. The 'spark plug' is heated either by the precise timing of imploding shocks or appropriately shaped laser pulses to introduce a slight amount of central pre-heating. This concept is typically modeled when, prior to the implosion process, the target contains a dense outer layer of D-T fuel and a central region of D-T gas. Then, as the capsule is compressed due to the ablation of the outer low-z shell, not only is the bulk of the fuel compressed on a low adiabat, but the cold fuel acts as a pusher which compresses the central region to the Lawson criterion of $\rho R \geq 0.3$ g/cm^2. It is generally advantageous to start the implosion with the majority of the fuel having as high density as possible (see: Larsen, 1989). High compression increases the fractional burn-up of the fuel as well as reducing the total fuel mass required for a given burn efficiency. Furthermore, *efficient* compression is enhanced when the starting condition is that of a shell of fuel, vs. that of a uniform spherical distribution of the same fuel, especially when laser-driven ablation efficiency is taken into consideration (Ashby, 1976). And although this may amount to no more than a factor of two or three, such improvements are crucial in planning a facility capable of achieving ignition such as the proposed U. S. National Ignition Facility (NIF), where the cost of the facility is roughly $1 billion to reach a peak laser energy of 1.8 MJ. In fact, at such high costs, even a ten or twenty percent savings on installed capacity will cover a substantial investment in additional technology to enhance the overall efficiency.

Is it any surprise then, that the target fabrication experts have turned on their charms to a low temperature physicist with no aversions to developing cryogenics for tritium? Not really, when you realize that cryogenics is about the only way of providing the 'magic' that the 'ideal' targets require. Knowing that his craft is capricious and often unwieldy, the good cryogenist first warns his new suitors that they should only consider cryogenic solutions when all other approaches have been exhausted. Indeed, he warns (ambiguously) that "cryogenics can *burn* you." However, in the case of ICF ignition, to be attained at a cost the modern world can afford, the cryogenic target appears to be a *sine qua non*. But then it's easy, isn't it? We just cool the target down to below ~25 K where the D-T fuel begins to condense to the liquid state, or further down below ~19.8 K where it freezes. Voila! A high starting density! Q. E. D. Yes, but we're only part way there. Remember they required a highly *symmetric*, *smooth* shell of fuel, not the puddle or the blob we've just formed in the bottom of the capsule. Don't forget that they need just the right density of gas in the center of the target. Then, again, the target designer may insist on using *plastic* as the wall material, which can't possibly hold the initial charge of gas at room temperature. Somehow, we've got to get all this into the precise center of the target chamber without interfering with the optical paths. Realizing that our work is cut out for us, we begin.

Cryogenic Fuel Layer Specifications

A good place to begin is with a review the specifications of the ICF target designers. The word 'specifications' used to be interchangeable with the phrase 'wish-list', simply because the idealities of the target theorist and the actualities of the target fabricator often were far apart. Hence, in practice, target specifications are often relaxed or compromised to deal with fabrications problems. This will continue to be true even with the targets for the OMEGA-Upgrade facility at the Laboratory for Laser Energetics at the University of Rochester, Rochester NY, USA (UR/LLE). This newly upgraded facility will begin operations in 1995 in an effort to evaluate the concept of direct-drive laser fusion, with an objective of high-gain target performance validation. But because the 30 kJ total incident energy of the 60-beam laser system is not high enough to achieve ignition, there may be some latitude in the as-delivered target specifications. A variety of different target designs are under consideration, but the cryogenic, high-gain target is currently specified to be a 1000 μm-diameter, 10 μm-thick plastic ablator shell containing a 100 μm-thick liquid or solid D_2 or D-T fuel layer. These targets are to be filled to pressures up to 1100 atm at room temperature (0.133 g/cm^3 for D-T), cooled to 25 K or below, and held at that temperature while they are layered and then shot. Once released from the pressurization apparatus, the targets must not be allowed to warm past ~30 K, because the internal pressure could burst the thin plastic shells. For D-T-filled targets, the desired central 'void' pressure is 0.3 mg/cm^3, which corresponds to the vapor pressure above the solid at 18.3 K.
However formed, the fuel layer symmetry must not deviate from perfection by more than ~ 3% of the average layer thickness d_0, "contained in l-modes 1 to 10." Let's take a minute to describe what we mean here. Typically, a spherical surface is characterized experimentally by measurements along an equatorial line and, for the sake of simplicity, axial symmetry is assummed. Then, the spherical surface can be described by expanding the radial coordinate $r(\theta)$ in Legendre polynomials: $r(\theta) = r_0 + \sum_{l=1}^{\infty} a_l P_l \cos(\theta)$, where a_l is the perturbation amplitude of the l^{th} harmonic mode. For our fuel layer shell, the amplitude of the l=1 mode describes the excess thickness δd of the shell at one point on the circumference (e.g. the bottom, for a liquid layer under the influence of gravity). Likewise, l-mode 2 describes the excess thickness mode which

has two maxima, 180 degrees apart (which might exist in a layer of liquid inside a spinning shell). The wavelength of mode 100, for example, is 1/100 of the circumference of the shell. Equivalently stated, the fuel layer symmetry for OMEGA-Upgrade targets must be better than 97%.

The OMEGA Upgrade specification for fuel layer symmetry matches that of the overall laser irradiation non-uniformity of 1% to 2%. The interior surface finish of the ablator shell, defined as the root mean sum (RMS) of the amplitudes of l-modes 2 through approx. 300, is specified to be better that 500 Å to limit the growth of Rayleigh-Taylor instabilities. Of course, the exterior of the fuel layer will be defined by this surface and not by any specific layering technique. However, the interior smoothness of the fuel layer, which is affected by the layering technique, is supposed to be of similar quality!

The cryogenic targets for NIF also must meet stringent requirements which probably *cannot* be relaxed if the goal of ignition is to be achieved. These targets will be roughly twice as large as those for the OMEGA-Upgrade, with a diameter of 2000 µm and a 100 µm-thick liquid or solid D-T fuel layer. The larger size permits a slightly larger roughness on the interior of the fuel layer of ~ 0.5 µm RMS summed over modes 2 to 100. Overall fuel layer symmetry may have to be better than 1% to 2 % to keep up with the better laser irradiation symmetry afforded by the indirect-drive configuration.

Fuel Layering Techniques

The techniques by which such symmetric, smooth fuel layers possibly can be prepared fall naturally into two categories, namely liquid layering techniques and solid layering techniques. In discussing these techniques, those which are applicable to both D_2 and D-T should get 'extra points', because although D-T is needed for ignition, many implosion physics experiments and diagnostic tests are better done with D_2 and hence many D_2-filled cryogenic targets will be needed in the various programs.

Liquid Layering Techniques

A Free Standing Liquid Layer

In the early days of the ICF program, when it was still believed that targets made by filling 100 µm-diameter glass microballons (GMB) with just a few hundred atmospheres of fuel would be sufficient for reaching high gain, Campbell (1974) showed that the natural slumping or 'sag time' of a D_2 or D-T liquid layer is just too short. His classical treatment showed that the time constant for slumping $\tau = 4 \cdot 10^{-2} \cdot D/d^2$ (µm · s), where D is the target diameter and d is the uniform liquid layer thickness, both in µm. For the 100 µm-diameter GMBs, $\tau = 4$ s for only a 1-µm-thick fuel layer! For the OMEGA-Upgrade target, $\tau = 4$ ms. So even if we could prepare a uniform liquid layer, it wouldn't last long!

A Freely Falling Target

Nor does it help to let a liquid-filled target simply fall freely into position, because, while the shape of the central gas space will quickly become spherical, there is no centering force on it and thus the liquid layer will always be asymmetric. However, it has been recently shown that a very thin layer may be so symmetrized due to the Van der Waals forces between the liquid and the shell walls (Parks and Fagaly, 1994).

Liquids in Foam Layers

However, by adding a shell of porous foam to the target, we can overcome some of these difficulties. The foam has to be such that it effectively wicks the liquid completely into the pores. Thus the pore size must be approximately 10 μm or smaller. There must also be no gaps between the foam and the shell wall larger than that of a pore, requiring some elegant fabrication procedures. To produce a very smooth interior surface, the foam layer may need to be slightly overfilled, reintroducing the slumping problems. The foam shell itself now becomes the critical issue, not the internal liquid. But the target fabricator is used to this sort of 'hand-off', where the responsibilities for target performance fall back on his shoulders. Consequently, much research has been invested recently in the fabrication of separate foam shells as well as spherical polymeric targets made complete with an internal foam layer.

Hollow foam shell targets have been developed for use with the 12-beam Gekko-XII glass laser at the Institute of Laser Engineering at Osaka University (ILE Osaka), Osaka, Japan (Norimatsu 1988). Polystyrene foam shells 700 μm to 1000 μm diameter were fabricated with walls 20μm to 50μm thick and 3μm to 30μm in pore size. Each shell was filled completely by being immersed into a pot of liquid D_2. Heaters controlled the thermal radiation from four viewing ports to the shell such that a filled shell would begin to generate D_2 vapor internally. This boiling forced the liquid out of the central void until only the foam shell itself was filled, whereupon the target was raised up out of the liquid bath and imploded. While such a technique is refreshingly novel, we would have to be concerned about the smoothness of the internal fuel layer surface, because by definition, the shell is underfilled. Also, open pools of D-T could require a considerable tritium inventory! The ILE Osaka group has also pioneered the development of composite shells with a solid external ablator shell and an integral foam layer (Takagi 1993). The outer ablator shells are of very high quality, with wall thicknesses of 1μm to 10μm, wall uniformity of 98% or better, and exterior surface smoothness of <0.1μm. The quality of the internal foam layer is not yet high enough to be useful for ignition experiments, but further work is in progress both at ILE Osaka, LLE Rochester, Lawrence Livermore National Laboratory (LLNL), and elsewhere, primarily because such targets could fulfill most of the requirements of D_2-filled targets.

Thermal Gradient Layering Technique

By far the most intriguing method of preparing a suitable liquid fuel layer is that known as the thermal gradient technique. As demonstrated experimentally by K. Kim (1987), a 200 μm-diameter GMB containing enough D_2 to make a uniform liquid layer ~4 μm thick was cooled by helium gas jets and subjected to a strong thermal gradient by superimposing a laser beam near the <u>bottom</u> of the shell The liquid fuel layer could be made to appear symmetric in shadow and interference microphotographs. This effect is due to a strong evaporation-condensation convection loop, made possible by the strong temperature dependence of the liquid vapor pressure. Kim further showed a larger (465 μm-diameter) glass shell filled with D-T to make a 4 μm-thick layer. This could also be made to appear uniform, but by imposing a smaller thermal gradient of the opposite sign, i.e., the top of the target was heated. This phenomenon is due to relative differences in surface tension effects in the two components and raises the possibility that the D/T ratio could differ considerably from bottom to top. (Whether this would be as detrimental to implosion symmetry as a few percent of mass unbalance has not been discussed.) Kim's results were reproduced by Gram (1990) at LLE Rochester, using heated jets instead of a laser to provide the temperature gradient. Working with a 250 µm-diameter glass shell filled with D-T to give a layer 6.0 µm-thick, Gram found that the symmetry was apparent in only one of the two viewing directions in his cryostat. To produce symmetry in both directions, he imposed a time-dependent thermal gradient. Hence, the thickness of the liquid layer oscillated from bottom to top, passing though a brief period of overall symmetry each half cycle. All of these experiments used relatively thin liquid layers. Much larger gradients would be needed to levitate the 100-µm-thick layers need for OMEGA Upgrade or NIF. Nevertheless, recent experiments at LLNL by Sanchez (1993) are showing some progress. Using NIF-sized targets, they have shown that a large amount of liquid can be pulled to the top of the target by applying heat to the top. However, the side walls remain covered by only a thin layer of liquid, and the layer structure oscillates uncontrollably. It is possible that such techniques are just not capable of supporting the thick vertical liquid wall needed to produce a symmetric liquid shell, even momentarily. Maybe one could add spin to the target shell to force liquid up the sides, but by then the whole concept starts to look questionable and unwieldy. Of course, if we could freeze the fuel layer at just the right time, we'd have it, wouldn't we?

Solid Layering Techniques

The Fast Isothermal Freezing Technique

That's just what KMS Fusion, Inc. (Musinski 1980) and others (Miller, 1978) were thinking when the fast isothermal freezing (FIF) technique was developed. Again working inside GMBs, it was demonstrated that by completely vaporizing a frozen mass of D_2 with a short laser pulse, the resulting re-freeze could be rapid enough to produce a symmetric shell, several microns thick. This effect capitalizes on the small heat of sublimation of solid hydrogens compared to the heat capacity of the GMB walls cooled to ~4 K. An overall uniformity of 90% (considered good in those days!) could be achieved if the fuel layer thickness was of order one micron. With so little fuel mass, the vapor condenses directly to the solid state. With slightly more material an intermediate liquid phase could form temporarily and thus sagging was observed in the final solid layer. Unfortunately, the interior surface finish was also frequently poor and irreproducible. By applying the laser heating pulse during free-fall, workers at the Lebedev Physical Institute in Moscow (Koresheva, 1991) have achieved 6-µm-thick uniform frozen layers inside GMBs of 500-µm to 800-µm in diameter. However, extending the technique of FIF to the larger targets needed today seems hopeless.

The Beta-Layering Phenomenon

But there is hope. It is called 'beta-layering'. It is not a technique because you don't have to do anything special. It is a phenomenon of nature that occurs when a self-heated solid with a high, temperature-dependent vapor pressure is held inside an isothermal chamber. Note that while these conditions do occur for D-T or T_2 inside an ICF target, there are very few other examples in nature (one is the lithophilic nature of natural uranium ores, another is the mobility of solid, radioactive iodine crystals.) It was first observed by this author (Hoffer, 1987), having been predicted by Miller (1975) and studied theoretically by Martin (1985). In the very first experiments, a 6-mm diameter copper-walled cylinder with sapphire end caps was filled ~25% full with pure tritium liquid (to avoid any complications due to isotopic fractionation). During freezing temperature to below the triple point, the T_2 formed an irregular, highly non-uniform solid layer on the bottom of the cylinder. Within several hours, the solid automatically redistributed itself into a smooth layer, nearly 400 μm-thick, uniform around the entire interior surface of the copper walls. The driving force for this phenomenon is the self-heating due to beta decay of tritium into ^{3}He. The beta-particles are recaptured by the solid, resulting in a parabolic thermal gradient in the solid layer. Because of this self-heating, thicker layers of solid DT tend to have warmer interior surfaces than do thinner ones. A net sublimation of material from the thicker sections to the thinner ones takes place with a reasonably rapid rate. Inside an isothermal enclosure, this results in the development of a D-T or T_2 shell of nearly perfectly uniform thickness.

Miller did not observe the phenomenon because the thickness of solid D-T in his target (~1 μm) was well below the 20 μm needed to absorb a sufficient fraction of the beta-particles. Furthermore, his target undoubtedly contained a significant fraction ^{3}He due to previous beta-decay. Because ^{3}He does not take part in the re-condensation of the fuel, it piles up near the solid boundary, thereby decreasing the rate of the process dramatically. Hoffer's group at Los Alamos (Simpson, 1992) has reported measurements of the rate constant of the beta-layering effect in both cylindrical and spherical geometries, using container materials of both high and low thermal conductivity, and using both fresh and aged D-T (where the amount of ^{3}He is significant). In general, the experiments are in excellent agreement with the theory of Bernat (1991), who, by extending Martin's treatment to properly account for the mutual diffusion of ^{3}He in D-T, showed that $\tau = H_S/q + \tau_3(^3He)$. In the leading term, H_S is the molar heat of sublimation of the fuel and q is the molar self-heating rate, which yields a time constant of 26.9 minutes for 'clean' (i.e., no ^{3}He present) 50-50 D-T at the triple point temperature of 19.8 K. The second term τ_3 accounts for the slowing-down due to the buildup ^{3}He of in the central vapor space. This term is strongly temperature and geometry dependent. For NIF targets, τ_3 amounts to ~3.5 minutes/day at 19.8 K (i.e., for every day of ^{3}He accumulation, the time constant for beta-layering increases by 3.5 minutes) and ~8.4 minutes/day at 18 K (Hoffer, 1990). To see just how good a beta-layered surface is, Fig. 1 shows an *l*-mode analysis of an image captured during our recent high-resolution optical investigations. (Not shown is the image itself - just imagine your first teething ring!) These data were measured in a 2000 μm-i.d. copper cylinder, machined to extremely high tolerances on an air-bearing lathe with diamond tooling. The lower set of data shows the spectrum of the empty bore and is representative of the resolution of this optical technique. Note that for the empty bore, no *l*-mode has an amplitude above 0.3 μm. The relatively high value of amplitude of mode 2 may be a result of a slight misalignment of the optics. The small mode 3 may be a remnant of the machinist's three-jawed collet! For the 139 μm-thick D-T layer shown in the upper trace, no mode is above 0.6 μm in amplitude. The sum of modes 1 through 10 is 1.3 μm, which meets the symmetry requirement of 99%. However, the sum of all modes is 1.7 μm, which is slightly too high for the desired surface roughness. (Note that the empty bore itself just meets the NIF requirement for surface finish!) The relatively high values for modes 6 to 20 are a result of the fact that in order to image the layer on the copper bore, the optical path also traverses layers of solid D-T on the sapphire end windows. By focusing directly on these window layers, we invariably observe optical defects due to crystal grain boundaries, for instance. Such defects affect our analyses, effectively raising the noise floor. Hence, there is a very good chance that the smoothness of the beta-layer is considerably better than we are now observing. Work is in progress to construct a cell wherein the layer of solid D-T on the windows can be burned off by local heating, thus permitting an unobstructed view of the beta-layer on the internal bore. In the

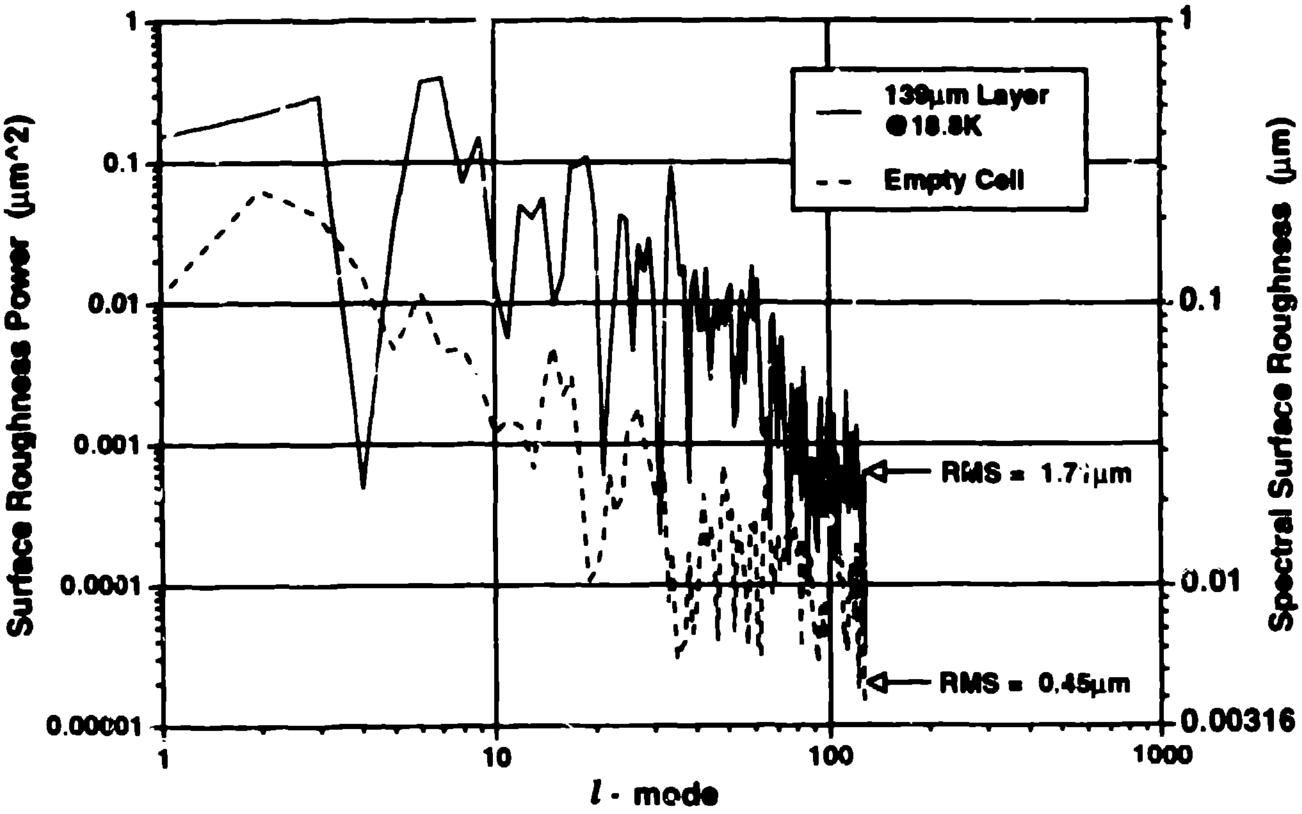

Fig. 1. Modal spectra of D-T solid layer and empty cylinder wall.

meantime, we leave it as 'highly likely' that the beta-layering phenomenon may produce the cryogenic target geometries with the high precision needed for ignition studies such as the NIF.

However, just in case that last statement is <u>not</u> true, there are a few things one could do to enhance the smoothness of the beta-layered solid D-T. Recall that beta-layering works because of uniform self-heating. This does not need to come from internal radioactive decay, but may be otherwise induced. One suggestion is infrared pumping of the rotational-vibrational bands. This would also work for D_2-filled targets, where there is no radioactive heating. Researchers at ILE Osaka (Chen, 1992) have shown that is sufficient to add heat only to the central vapor space by, e.g., inducing a plasma discharge. This also produces the internal temperature gradient (hotter inside, colder outside) needed to induce symmetrization. Adding only a modest amount of additional internal heating to a beta-layered shell could speed the process and possibly produce considerably smoother surfaces. Collins (1993) has demonstrated that a heat flux entering the surface smoothes solid H_2 and HD layers. It may prove difficult to achieve a discharge in cold D_2 gas, but the presence of free beta-particles in a D-T mixture may permit the generation of a low-energy plasma discharge.

Summary

The phenomenon of beta-layering can be used to produce symmetric solid layers of D-T, but the interior surface finish may need to be enhanced by a technique such as plasma heating. If a low-energy plasma discharge can be sustained in pure D_2 gas, it might be possible to produce solid D_2 targets as well. Neither this nor any other technique for symmetrizing thick layers of solid D_2 has been demonstrated.

Presently, symmetric layers of pure liquid D_2 or D-T in the 100-μm thicknesses required cannot be fabricated by any known technique. However, the use of high-quality foam shells would make liquid targets possible. To enhance ignition, the foam may need to be slightly overfilled, requiring further symmetrization techniques, such as free fall, magnetic levitation, or thermal gradients.

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